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Pre-sowing magnetic treatment of tomato seeds: effects on the growth and yield of plants cultivated late in the season

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Abstract

The effects of pre-sowing magnetic treatments on the growth and yield of tomatoes (cv. Vyta), cultivated late in the season, were studied under field conditions. Tomato seeds were exposed either to a 120 mT dynamic magnetic field (induced by an experimental electromagnet) for 10 min or to a 80 mT field for 5 min. Non-treated seeds were used as controls. Plants were grown in experimental plots (20.2 m^2) and cultivated according to standard agriculture practices. At physiological maturity, the plants were harvested from each plot and the number of fruits, mean fruit weight, fruit yield per plant and fruit yield per area determined. In the nursery stage, the treatments led to a significant increase in root length, fresh and dry root weight, stem length, fresh and dry stem weight, leaf area and foliole dry weight. During the vegetative stage, the leaf, stem and root relative growth rates of plants derived from magnetically-treated seeds were greater than those shown by control plants. In the generative stage, the relative growth rate of the fruits belonging to the 'magnetically treated plants' was greater than that of control plant fruits. At the fruit maturity stage, the magnetically treated seeds produced plants with significantly more fruits (17.9-21.3%), with a significantly greater mean fruit weight (22.3-25.5%), and with a greater fruit yield per plant (47.3-51.7%) and per area (48.6-50.8%) than did the control plants. Pre-sowing magnetic treatments would appear to enhance the growth and yield of tomatoes cultivated late in the season.

Additional key words: dry matter increase, *Lycopersicon esculentum*, magnetic field, stimulating effect.

Resumen

Incremento del crecimiento y rendimiento del tomate por tratamientos magnéticos de semillas en época tardía

Se estudiaron los efectos de tratamientos magnéticos presiembra sobre el crecimiento y rendimiento del tomate (cv Vyta), cultivado en período tardío en condiciones de campo. Las semillas de tomate se expusieron a campos magnéticos de 120 mT durante 10 min y 80 mT durante 5 min en un eletroimán experimental, utilizando simultáneamente semillas sin tratamiento como control. Las plantas se sembraron en parcelas experimentales (20,2 m^2) y se cultivaron de acuerdo con las prácticas agrícolas normales. En la madurez fisiológica, se determinó el número de frutos por planta, la masa promedio de los frutos y el rendimiento por planta y área. En la etapa de semillero, los tratamientos indujeron un incremento significativo de la longitud, masa fresca y seca de la raíz, longitud; masa fresca y seca del tallo; área foliar y masa seca foliar por foliolo. Durante la etapa vegetativa, las tasas relativas de crecimiento de las hojas, tallos y raíces fueron significativamente superiores en los tratamientos magnéticos que en el control, mientras que en la etapa generativa, solamente resultaron significativas las tasas de crecimiento relativo de los frutos. En la etapa de madurez de los frutos, los resultados revelaron que ambos tratamientos magnéticos incrementaron significativamente el número de frutos por planta (17,9-21,3%), masa promedio de los frutos (22,3-25,5%), rendimiento por planta (47,3-51,7%) y rendimiento por área (48,6-50,8%) comparados con el control. Nuestros datos indican que los tratamientos magnéticos mejoraron el crecimiento y rendimiento del tomate cultivado en período tardío.

Palabras clave adicionales: campo magnético, efecto estimulante, incremento de materia seca, *Lycopersicon esculentum*.

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Introduction

All living organisms evolved in the presence of a natural geomagnetic field; determining the influence that magnetic fields might have on organisms is now the subject of an increasingly large research effort. It is thought that plants might respond to magnetic fields by showing greater growth and productivity. At the cellular level, a wide range of physiological effects can be observed. Magnetic fields have been reported to exert a positive effect on the germination of seeds (Alexander and Doijode, 1995; Carbonell *et al.,* 2000), on plant growth and development (De Souza *et al.,* 1999; Martínez *et al.,* 2000), on tree growth (Ruzic *et al.,* 1998), on the ripening of fruits and vegetables (Boe and Salunke, 1963) and on crop yield (Pietruszewski, 1993); some review papers also mention a number of controversial, early results (Findlay and Hope, 1976; Frey, 1993). Several models have been proposed to explain the possible mechanisms behind the influence of magnetic fields and to predict the magnetic exposure conditions that might produce biological effects (Lednev, 1991; Popp, 1994). However the effects that have been reported do not seem to be easily explained by a single hypothesis.

Extensive research has revealed that the effects of magnetic treatments depend not only on the magnetic field strength and exposure period (Wittekind *et al.,* 1990), but also on the physiological condition of the organism involved, and on the reigning environmental conditions (Weaver, 1993; Gutzeit, 2001). Basic stimulating doses (based on magnetic field strength and exposure period) must therefore be established under controlled conditions before using them with plants to be grown in the field (Jristova, 1986).

The aim of this study was to determine the effects of pre-sowing magnetic treatments on tomato (cv. Vyta) plant growth (late season cultivation under field conditions) during the nursery, vegetative and generative stages, and on final yield and yield variables.

Material and Methods

Plant material

The tomato seeds (*Lycopersicon esculentum* Mill. cv. Vyta) used in the present experiments were genetically uniform and had a moisture content of 9-10%. All were provided by the Seeds Laboratory of the Ministry of Agriculture, Granma Province, Cuba.

Magnetic exposure conditions

The pre-sowing magnetic treatments were administered using an electromagnet. This consisted of two pairs of energizable, cylindrical coils, each formed by 4,026 turns of 0.41 mm enamelled copper wire. Each pair of coils was wound 11 cm apart on an iron bar (dimensions 40 × 3.5 cm). The two bars were placed one above the other, their ends held by metallic supports (Fig. 1). The coils were connected in series and fed a rectified sinusoidal voltage to reach a full wave with an effective value of 200 volts.

When electric current passed through the coils, a non-uniform and dynamic magnetic field was generated in the air space between the two bars. This was adjusted by moving one of the bars up or down (using a mechanical system) until the required working strength was achieved. The fields generated in the air space between the two bars were measured using a micrometer positioning system coupled to a 410-HCAT Lakeshore magnetometer at 25ºC.

No magnetic field other than that of the geomagnetic field was detected within the experimental electromagnet when switched off. The local geomagnetic field within the coils was approximately 61 μT (microTesla). The local geomagnetic components were $B_v = 25$ μT, $B_H = 20$ μT; the declination and inclination angles were 0° and 51.5° respectively.

Tomato seeds were placed in Petri dishes (9 cm in diameter) in the space between the two bars of the electromagnet, and the following magnetic treatments provided: T1, exposure to a dynamic magnetic field of 120 mT for 10 min; T2, exposure to a dynamic magnetic field of 80 mT for 5 min; control: exposure to the local geomagnetic field only.

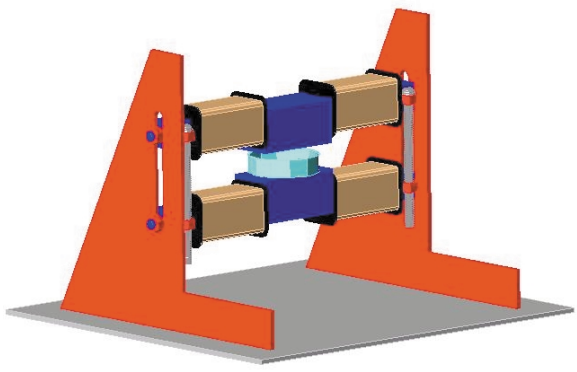

Figure 1. The experimental electromagnet apparatus. A Petri dish is placed in the air gap between the two iron bars to expose the seeds to the magnetic fields.

The choice of the above magnetic treatments was made from previous controlled laboratory and greenhouse conditions (De Souza, 2002).

Field conditions

The seeds were sown in seed beds (15 cm deep) on 12th January, 2002 before transplant into the open field. These seeds were sown 6 cm apart and 0.5 cm deep in rows at a rate of 1.2 g seeds m^{-2}, according to standard agricultural practice. During this period, water was provided every day during the morning.

During the nursery stage, 20 seedlings per treatment were sampled at 15 and 25 days post-sowing and their length, the fresh and dry weight (ventilated oven; 80°C for at least 72 h) of their leaves (including petioles), stems and roots, and the leaf area per foliole (Mk2, Delta-T Devices Areameter, Cambridge, UK) determined.

At 28 days post sowing (9th February of 2002), the seedlings were manually transplanted (naked root) to experimental field plots at the Agricultural Research Institute «Jorge Dimitrov». The plots (20.2 m^2) were 5.6 m long and 3.6 m wide and comprised of five rows 1.40 m apart. A border row was included around each plot to reduce the spread of pests and diseases. Plots were arranged in a randomised complete block design with four replicates per treatment for a total of 12 plots. Sixty seedlings spaced 0.30 m apart (within-row spacing) were transplanted to each plot. Thirty were sown in the central area for further sampling, while the rest (30 seedlings) were planted in the border area. Thus, a total of 720 plants were cultivated, of which 360 were analysed. Cultivation operations were performed manually, paying special attention to sowing, weeding and harvesting procedures, following the standard agricultural practices established for tomato crops by the Ministry of Agriculture (MINAG, 1995).

The soil in the plots was an Entropept (Soil Survey Staff, 1994) derived from calcareous materials. The texture of the upper layer (0-0.20 cm) was that of a clay. Table 1 provides information on the soil's macro- and micronutrient contents and its chemical and physical properties. The experiment was conducted under low input conditions, i.e., with no application of mineral and/or organic fertilizers, with no pesticides, and with minimum ground working. According to the soil analysis performed, plant nutrient levels were adequate for the growth of tomatoes.

Irrigation was provided uniformly to all plots using a stationary sprinkler system. The first and second irrigations were provided before and after transplanting at 0.12 $m^3\ m^{-2}$. The same amount was then provided daily for 20 days. After this time, irrigation was performed at intervals of 3 days (0.24 $m^3\ m^{-2}$) for 70 days, and finally at intervals of 5 days (0.36 $m^3\ m^{-2}$) for 30 days until the crop had completed its cycle. Irrigation was stopped one week before harvest.

Weather data for the experimental period were recorded by the meteorological station at Bayamo (Table 2).

Growth dynamics and yield

The growth dynamics of the crop were divided into two different phases: vegetative (before the appearance of the reproductive organs) and generative (the formation of flowers, anthesis, and the development of fruits). Crop growth dynamics were assessed in the four plots (one plot = one replicate) corresponding to each treatment. Every 15 days, five plants per treatment were

Table 1. Macro- and micronutrient contents and chemical and physical properties of the Entropept soil in the experimental plots at the Agricultural Research Institute «Jorge Dimitrov»

Macronutrients		Micronutrients		Chemical and physical properties	
Organic matter (%)	3.2	Fe (meq 100-g^{-1})	150.1	P_2O_5 (%)	0.05
Organic carbon content (%)	5.52	Mn (meq 100-g^{-1})	5.13	K_2O (%)	0.73
Na (meq 100-g^{-1})	0.49	Zn (meq 100-g^{-1})	0.65	pH (water)	6.40
Ca (meq 100-g^{-1})	30.20	Cu (meq 100-g^{-1})	0.11	pH (KCl)	6.32
K (meq 100-g^{-1})	0.22	Mo (meq 100-g^{-1})	0.18	Base exchange capacity (meq 100-g^{-1})	38.62
Mg (meq 100-g^{-1})	7.71	B (meq 100-g^{-1})	0.45	Cation exchange capacity (meq 100-g^{-1})	41.28
P (meq 100-g^{-1})	0.12	Cl (meq 100-g^{-1})	0.10	Hydrolytic acidity (meq 100-g^{-1})	1.3
				Soil moisture (%)	3.0
				Bulk density (g cm^{-3})	0.98

Table 2. Climatic conditions during the experimental period

Meteorological variables	January	February	March	April	May
Mean maximum temperature (°C)	28.1	31.6	32.3	33.0	32.1
Mean minimum temperature (°C)	15.5	16.8	17.0	19.7	21.1
Mean temperature (°C)	21.2	23.6	24.2	26.0	25.7
Light (hours)	12	14	14	14	14
Relative humidity (%)	81	77	76	72	82
Average rainfall (mm)	24	27	30	44	61
Speed wind (m s^{-1})	9.8	10.2	12.4	15.7	9.8

randomly selected for measuring different variables (a procedure that destroyed the sampled plants); this was performed over a period of 105 days post-transplant (and therefore involved 120 plants). Variables similar to those measured in the nursery stage were determined for growth analysis, including the dry weight (ventilated oven; 80ºC for at least 72 h) of picked fruits and the specific leaf area (SLA). The relative growth rates (RGR, g g^{-1} day^{-1}) of leaves, stems, roots and fruits were determined from the slopes of graphs for dry weight (natural logarithms) *versus* time between individual sampling dates (Hunt, 1990).

In the flowering stage, 20 plants per treatment were labelled and the number of open flowers per plant counted. The percentage of fruit set was later calculated from this figure and the number of fruits recorded during the fruiting stage.

At physiological maturity, 20 plants from the central rows of each plot were labelled, representing an area of 8.4 m^2 (i.e., 80 plants per treatment – 240 in all). As the fruits were harvested, the number provided per plant was recorded. Mean fruit weight (g), mean fruit yield per plant (kg per plant) and mean fruit yield per area (kg m^{-2}) were then calculated. Harvesting was performed on five dates, once every seven days. Fruit yield per plant was calculated by multiplying the mean fruit weight by the number of fruits per labelled plant at each harvest. The plantation area (0.42 m^2), calculation area (8.4 m^2) and fruit yield per plant at each harvest were used to calculate the fruit yield per area (kg m^{-2}).

Data analyses

Data for the nursery stage, the growth dynamics during the vegetative and generative stages, and the yield and yield variables were pooled for each harvest and analysed by two-way ANOVA ($p < 0.05$) to determine the effects of the magnetic treatments. Means were compared using the Newman-Keuls test (Stell and Torrie, 1992). The Kolmogorov-Smirnov procedure was used for data testing normality; Bartlett's test was used to test the homogeneity of variances among treatments (Yandell, 1997). All statistical analyses were performed using the Statistica software package (StatSoft, Tulsa, OK).

Results

Nursery stage

The magnetic treatments had a significant effect ($p < 0.05$) on root length, which increased by 17.5% with the T1 treatment and by 18% with T2 compared to controls (Table 3). Similarly, these treatments had a remarkable effect ($p < 0.05$) on root fresh and dry weight results: T1 treatment led to an increase in fresh weight of 48.2 % while T2 led to a 38.6% increase; root dry weight increased by 80.7% with T1 and by 79.1% with T2 (Table 3).

Stem length was also significantly affected by the magnetic treatments ($p < 0.05$); T1 led to a 34.9% increase while T2 led to a 35.9% increase over that of the controls (Table 3). The treatments also led to significantly ($p < 0.05$) greater stem fresh and dry weights: T1 increased stem fresh weight by 39.6 % while T2 increased this by 32.2%; similarly, stem dry weight increased by 75.4% in T1 plants and by 60.4% in T2 plants (Table 3).

The magnetic treatments had a positive effect ($p < 0.05$) on leaf area per foliole and dry weight. Leaf area per foliole increased by 39.3% with T1 and by 22.8% with T2 (Table 3); leaf dry weight was significantly increased by 26.7% with T1 and by 18.8% with T2 (Table 3).

Table 3. Effect of pre-sowing magnetic treatments on growth variables of tomato Vyta in the nursery stage (25 days after sowing). Data are means of 20 plants per treatment

Growth parameters	T1 (120 mT for 10 min)	T2 (80 mT for 5 min)	Control	CV (%)
Root length (cm)	10.53 ± 0.17[a]	10.58 ± 0.18[a]	8.96 ± 0.15[b]	9.6
Root fresh weight (g)	0.406 ± 0.019[a]	0.380 ± 0.016[a]	0.274 ± 0.017[b]	17.7
Root dry weight (g)	0.0667 ± 0.0038[a]	0.0661 ± 0.0036[a]	0.0369 ± 0.0033[b]	17.5
Stem length (cm)	30.86 ± 0.76[a]	31.07 ± 0.74[a]	22.86 ± 0.077[b]	14.8
Stem fresh weight (g)	5.85 ± 0.24[a]	5.54 ± 0.20[a]	4.19 ± 0.22[b]	11.5
Stem dry weight (g)	0.586 ± 0.027[a]	0.536 ± 0.025[a]	0.334 ± 0.024[b]	18.6
Leaf area per foliole (cm^2)	6.98 ± 0.29[a]	6.15 ± 0.26[a]	5.01 ± 0.27[b]	15.1
Leaf dry weight (g)	0.0450 ± 0.0020[a]	0.0422 ± 0.0017[a]	0.0355 ± 0.016[b]	17.7

The same letter within a row indicates the lack of a significant difference ($p < 0.05$) according to the Newman-Keuls test. CV: coefficient of variation.

Vegetative and generative stages

At the vegetative stage, the plants derived from seeds treated with magnetic fields showed a significantly greater leaf area per plant and leaf dry weight than did the controls. T1 plants showed an increase of 64.5% in leaf area while T2 showed an increase of 60.9%; similarly, T1 plants showed a 51.6% increase in leaf dry weight while T2 showed a 49.8% increase (Table 4). This resulted in an increase in SLA of 9.5% for the T1 and 8.5% for T2 plants compared to the controls (Table 4).

At the generative stage, leaf area per plant and SLA were significantly increased ($p < 0.05$) by the magnetic treatments. T1 plants showed increases of 56.2% and 7.6% respectively, while T2 plants showed increases of 55.6% and 7.2% respectively (Table 4). Leaf dry weight per plant, however, was not influenced by the magnetic treatments at this stage.

Relative growth rates (RGR) express growth in terms of the increase in dry weight per unit of total weight and time. Figures 2, 3 and 4 show the RGR means for two growth stages ranging over the period of stem elongation to the development of fruits.

Differences in growth dynamics between the vegetative stage (before the appearance of the reproductive organs) and the generative stage (the formation of flowers, anthesis and the development of fruits) were found between the treated and control plants. At the vegetative stage, the T1 and T2 plants showed RGRs for the leaves some 20.6% and 18.5% greater than that of the controls. The same was seen for their stems (14.4% and 12.7% respectively) and roots (19.5% and 15.4% respectively) ($p < 0.05$ for all comparisons) (Fig. 2). However, at the generative stage, only the RGRs of the fruits were higher (53% for T1 and 40% for T2) than those shown by the

Table 4. Effect of pre-sowing magnetic treatments on leaf variables in the vegetative and generative stages. Data are means of 60 plants per treatment

Leaf parameters	T1	T2	Control	CV (%)
Vegetative stage				
Leaf area per plant (cm^2)	2652 ± 165[a]	2594 ± 160[a]	1612 ± 167[b]	24.2
Leaf dry weight (g)	9.86 ± 1.2[a]	9.74 ± 1.0[a]	6.50 ± 1.0[b]	23.7
Specific leaf area ($cm^2\ g^{-1}$)	270.9 ± 5.0[a]	268.3 ± 4.7[a]	247.2 ± 4.8[b]	4.8
Generative stage				
Leaf area per plant (cm^2)	4950 ± 175[a]	4934 ± 170[a]	4105 ± 172[b]	21.4
Leaf dry weight (g)	14.90 ± 1.6[a]	14.80 ± 1.3[a]	13.20 ± 1.5[a]	21.7
Specific leaf area ($cm^2\ g^{-1}$)	334.2 ± 5.8[a]	333.0 ± 6.0[a]	310.4 ± 5.6[b]	4.2

The same letter within a row indicates the lack of a significant difference ($p < 0.05$) according to the Newman-Keuls test. CV: coefficient of variation.

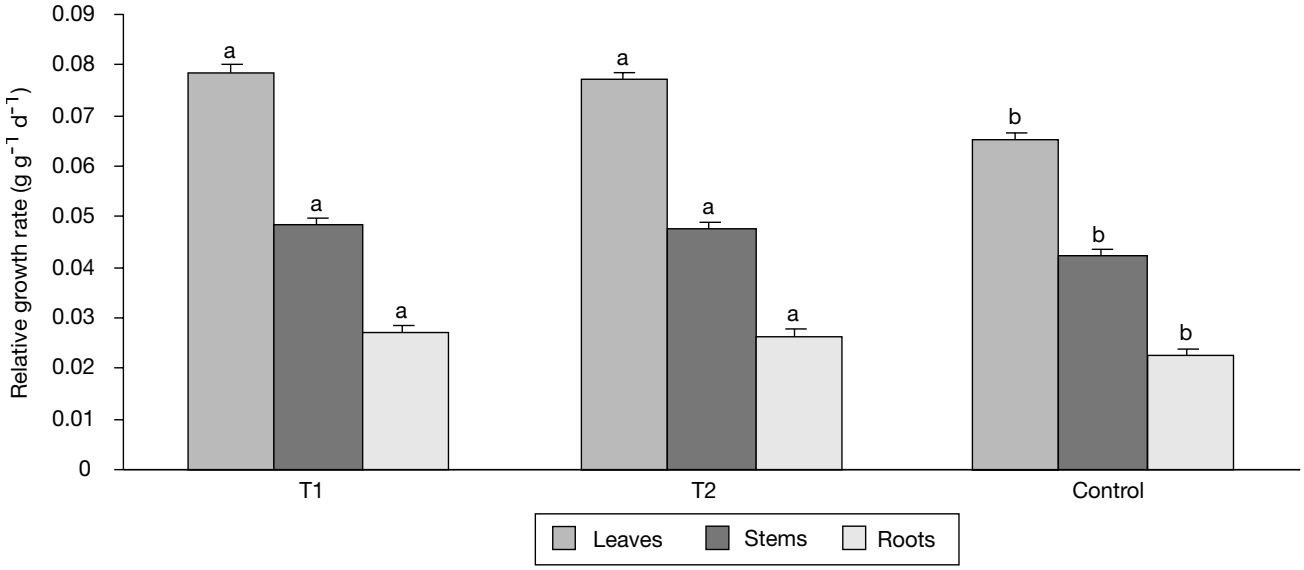

Figure 2. Influence of pre-sowing magnetic treatments on relative growth rates (RGR) of leaves, stems and roots during the vegetative stage. The same letter in bars for each variable indicates the lack of a significant difference ($p < 0.05$) according to the Newman-Keuls test. I: represents the average standard error of the means.

controls ($p < 0.05$) (Fig. 4). The RGRs of the leaves, stems and roots were unaffected ($p < 0.05$) by magnetic treatments at this stage (Fig. 3).

The number of open flowers per plant and the percentage of fruit set were significantly influenced ($p < 0.05$) by the magnetic treatments. Increases of 22.4% and 19.3% were seen in number of open flowers for T1 and T2 plants respectively, as well as an improvement of 8.8% and 7.9% in fruit set (Table 5).

At the end of the experiment, the total dry matter of the plants derived from the magnetically treated seeds was significantly greater (31.1-33.6%) than that of the control plants (Table 6).

The final dry weights of the leaves, stem and fruits were significantly higher for the treated than for the

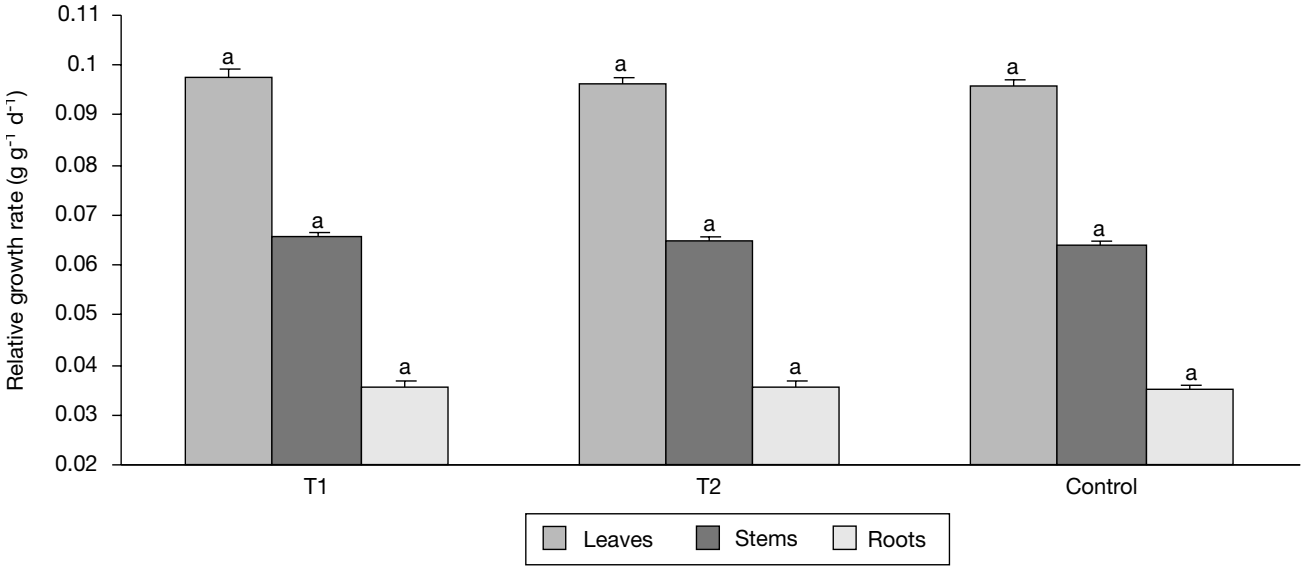

Figure 3. Influence of pre-sowing magnetic treatments on relative growth rates (RGR) of leaves, stems and roots during the generative stage. The same letter in bars for each variable indicates the lack of a significant difference ($p < 0.05$) according to the Newman-Keuls test. I: represents the average standard error of the means.

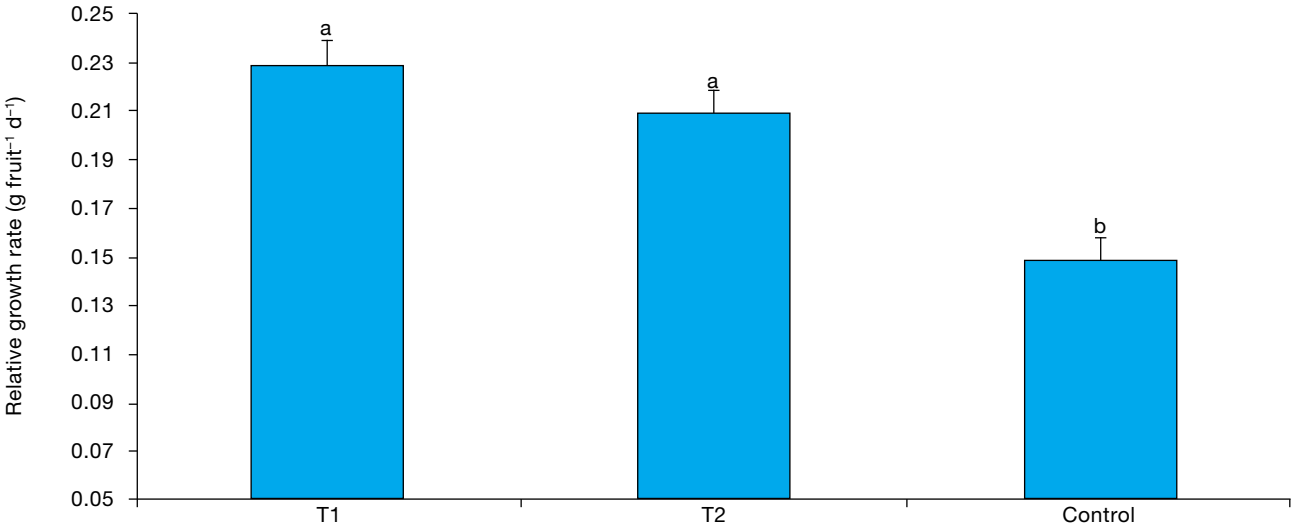

Figure 4. Influence of pre-sowing magnetic treatments on relative growth rates (RGR) of fruits. The same letter in bars indicates the lack of a significant difference ($p < 0.05$) according to the Newman-Keuls test. I: represents the average standard error of the means.

control plants ($p < 0.05$). Further, their fruit dry matter production was greater than their leaf dry matter production, which in turn was greater than their stem dry matter production (Table 6). In the treated plants at 105 days after transplanting, 61% of the total dry matter had been distributed to the fruits, 27% to the leaves and 12% to the stem. In the control plants, 54% of total dry matter had been distributed to the fruits, 33% to the leaves and 13% to the stem (Table 6).

Crop yield

The number of harvested fruits per plant was significantly influenced ($p < 0.05$) by the pre-sowing

Table 5. Effect of pre-sowing magnetic treatments on generative variables. Data are means of 20 plants per treatment

Generative parameters	T1	T2	Control	CV (%)
Number of open flowers per plant	28.4 ± 0.60[a]	27.7 ± 0.64[a]	23.2 ± 0.70[b]	9.9
Number of fruits per plant	24.8 ± 0.65[a]	24.3 ± 0.61[a]	18.6 ± 0.68[b]	14.5
Fruit set (%)	87.3[a]	86.6[a]	80.2[b]	4.1

The same letter within a row indicates the lack of a significant difference ($p < 0.05$) according to the Newman-Keuls test. CV: coefficient of variation.

Table 6. Effect of pre-sowing magnetic treatments on final dry weights of leaves, stem, and fruits. Data were collected 105 days after transplanting. The contribution (%) of leaves, stem and fruits to the total dry weight is given in brackets

Final dry weights (g m^{-2})	T1	T2	Control	ASE	CV (%)
Leaf dry weight	312 (27)[a]	304 (27)[a]	280 (33)[b]	8.2	5.8
Stem dry weight	131 (12)[a]	125 (12)[a]	108 (13)[b]	4.7	9.6
Fruit dry weight	690 (61)[a]	683 (61)[a]	460 (54)[b]	12.0	19.3
Total dry weight	1,133[a]	1,112[a]	848[b]	20	38.8

The same letter within a row indicates the lack of a significant difference ($p < 0.05$) according to the Newman-Keuls test. CV: coefficient of variation. ASE: average standard error of mean.

Table 7. Effect of pre-sowing magnetic treatment on crop yield. Data are means of 80 plants per treatment

Variables measured	T1	T2	Control	CV (%)
Number of harvested fruits per plant	21.6 ± 0.80[a]	21.0 ± 0.82[a]	17.8 ± 0.70[b]	9.8
Mean fruit weight (g)	79.09 ± 4.80[a]	77.03 ± 4.0[a]	62.98 ± 4.30[b]	12.8
Fruit yield (kg) per plant	1.70 ± 0.30[a]	1.65 ± 0.25[a]	1.12 ± 0.20[b]	26.7
Fruit yield per area (kg m^{-2})	34.1 ± 4.0[a]	33.6 ± 3.2[a]	22.6 ± 3.1[b]	23.1

The same letter within a row indicates the lack of a significant difference ($p < 0.05$) according to the Newman-Keuls test. CV: coefficient of variation.

magnetic treatments; T1 plants showed an increase of 21.3% while T2 plants showed an increase of 17.9% over figures for the controls (Table 7).

The magnetic treatments had a significant effect on mean fruit weight (increases of 25.5% and 22.3% for T1 and T2 respectively; Table 7).

Fruit yield per plant was also significantly influenced ($p < 0.05$) by the magnetic treatments, with increases of 51.7% and 47.3% for T1 and T2 respectively (Table 7).

Fruit yield per area was remarkably increased ($p < 0.05$) by the treatments, with increases of 50.8% and 48.6% for T1 and T2 respectively (Table 7).

Discussion

Exposing the tomato seeds to the magnetic fields led to a considerable improvement in the growth and early development of the plants they produced.

The results show the magnetic treatments led to a remarkable increase in plant root and stem length as well as fresh and dry weight during the nursery period. These initial effects are very positive since they appear to induce an improved capacity for nutrient and water uptake, providing greater physical support to the developing shoot. Better root growth and development in young seedlings might lead to better root systems throughout the lifetime of a plant (Leskovar and Stoffella, 1995; Lynch, 1995). The improvement induced by the magnetic treatment was consistent with the results of other studies (Phirke *et al.,* 1996; Amaya *et al.,* 1999) which also report enhanced root and stem growth and fresh weight in tomato plants.

The enhancement in leaf area and leaf dry weight in the plants derived from the treated seeds must have increased photosynthetic rates due to the greater interception of light and the greater amount of assimilates available for vegetative growth. This resulted in an increased SLA, which had a strong influence on crop growth. This agrees with the results of Hoff (1981) and Davies (1996), who found an increase in photosynthetic rate and influx of water as a result of magnetic treatments. Socorro *et al*. (1999) also reported a positive effect of magnetic treatment on leaf thickness in crop tomatoes, leading to a noticeable increase in the thickness of the spongy tissue, and in the length and width of chlorophyll-containing cells and the upper and lower epidermal cells.

The magnetic treatments had positive effects on the RGR of the leaves, stems and roots during the vegetative stage, and on the RGR of fruits during the generative stage. This would favour crop metabolic activity and lead to an increase in the quantity of assimilates available for growth, initial and final development, and distribution (dry matter) among the plant organs. The results showed that the magnetic treatments stimulated dry matter production and improved its partitioning.

The lack of influence of magnetic treatment on the leaves, stems and roots during the generative stage may be explained in the greater dry matter gain induced in the developing fruits (Fig. 4). This is the main physiological process at this stage of growth. Nutrient uptake for fruit growth is greater during this part of the life cycle, during which vegetative growth stops.

The improvement in dry matter partitioning to the fruits in plants derived from seeds exposed to magnetic fields was, to a great extent, determined by the number of fruits on the plants (Table 7). The smaller fraction of dry matter distributed to the fruits in control plants was probably due to poor fruit setting, which was compensated for by increased vegetative growth. The partitioning of the dry matter to the fruits recorded in this work was lower than that recorded by De Koning (1993) for a commercial tomato crop raised over the full growing season (72%).

The fact that the number of open flowers and fruits set per plant were positively influenced by magnetic treatment suggests that it might, in some way, reduce

flower and/or fruit abortion. The remarkable improvement in fruit yield per plant and per area resulted from an increase in the number of harvested fruits per plant and mean fruit weight induced by the magnetic treatments. Similar effects have been reported on buckwheat, sunflower, flax, pea, wheat, pepper, tomato, soybean, potato and sugar beet yields by Gubbels (1982), Pietruszewski (1999), Takac *et al*. (2002), Crnobarac *et al.* (2002) and Marinkovic *et al.* (2002).

The effects of magnetic exposure on plant growth still require proper explanation. They may be the result of bioenergetic structural excitement causing cell pumping and enzymatic stimulation. Jones *et al.*(1986) propose that magnetic fields might affect the regulation of crucial ion mechanisms, such as the ATP hydrogen pump, and possibly the configuration of pivotal proteins. Kuzin *et al.* (1986) suggests that magnetic fields modulate the rate of recombination of free radicals during normal plant metabolism. Other authors suggest that magnetic fields might affect the activity of ion channels (Galt *et al.,*1993) or ion transport within cells (Garcia-Sancho and Javier, 1994). However, the basic mechanisms responsible for the magnetic stimulation of plant growth remain a mystery.

In conclusion, the present results indicate that presowing magnetic treatments of 120 mT for 10 min or 80 mT for 5 min enhance the growth and development of tomato plants, and improve their fruit yield and other yield variables.

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